

Hadronic γ -ray emission models

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Models for γ -ray emission from active galactic nuclei (AGN) based on hadronic interactions have in the past considered interactions between relativistic protons and matter in an accretion disk surrounding a black hole. However, it has become evident that γ -rays originate in relativistic jets in which the matter density is too low to provide the required target matter for relativistic protons. The density of photons, on the other hand, is large enough to cool relativistic protons efficiently provided their energy exceeds the threshold for secondary particle production (pairs, pions, kaons, ...). In spite of the hadronic cross-section $\sigma_{p\gamma} = 5 \cdot 10^{-28} \text{ cm}^2$ being much smaller than the Thomson cross-section $\sigma_T = 6.7 \cdot 10^{-25} \text{ cm}^2$, the proton cooling time scale can be as short as the electron cooling time scale. Comparing pion photo-production by protons with inverse-Compton scattering of electrons on the same photon target with photon density $n_\gamma \propto \epsilon^{-1}$, one obtains

$$\frac{t_p}{t_e} \simeq \frac{n_\gamma(\epsilon) \frac{\epsilon}{m_e c^2} \gamma_e \sigma_T c}{n_\gamma \left(\frac{m_\pi c^2}{\gamma_p} \right) \frac{m_\pi}{m_p} \sigma_{p\gamma} c} = \frac{m_p}{m_e} \frac{\gamma_e}{\gamma_p} \frac{\sigma_T}{\sigma_{p\gamma}} \approx 2.5 \cdot 10^6 \frac{\gamma_e}{\gamma_p}, \quad (1)$$

i.e. $t_p = t_e$ for $\gamma_p = 2.5 \cdot 10^6 \gamma_e$. Consequently, the proton-induced luminosity given by

$$L_p \simeq \frac{u_p}{u_e} \frac{t_e}{t_p} L_e \quad (2)$$

can exceed the Compton luminosity by a large factor (e.g., the relativistic proton-to-electron energy density ratio in the Galaxy is $u_p \approx 100 u_e$). In a statistical acceleration process such as Fermi acceleration at shock waves, acceleration operates until energy losses (or geometrical constraints) become important implying much larger proton than electron maximum energies. Photoproduction by shock-accelerated protons in a relativistic jet at some distance to the central black hole is assumed in the models of Protheroe (1996a,b) and Mannheim (1993a).

These models assume different target radiation spectra. Protheroe assumes a disk spectrum, whereas a synchrotron spectrum is assumed in the latter model. The disk spectrum is expected to be more important if particle acceleration occurs at distance less than a parsec from the central black hole and the synchrotron spectrum dominates at larger distances. If there is continuous proton acceleration along the jet, both targets fields

are important. Shock acceleration of particles outside of the central parsec is expected to accompany the passage of the supersonic jet through the steep external pressure gradient characterizing the external medium beyond the Broad Line Region. Some jet formation models predict magnetic collimation to a cylindrical flow with a transverse radius of the order of $r_j \sim 100r_G = 3 \cdot 10^{15} m_8$ cm. If the collimation can be maintained over a parsec, rapid variability is possible even in the synchrotron target model on time scales of the order of $\sim r_j/(\delta_j c) \sim 10^4 \delta_{10} m_8$ s where m_8 denotes black hole mass in units of $10^8 M_\odot$ and δ_j is the jet Doppler factor in units of 10.

Both models find that the γ -ray spectra from hadronic synchrotron cascades can explain the observed properties of γ -ray emitting AGN. They also predict very similar diffuse neutrino fluxes from the sources. If γ -ray emitting AGN produce the isotropic diffuse γ -ray background, the corresponding neutrino background at high energies can be detected by a cubic-kilometer underice muon detector. The models further agree that (comoving frame) proton energies in the range $10^8 - 10^{10}$ GeV are required to explain the observations. At perpendicular relativistic shocks, the maximum rate of energy gain is $\dot{E} \sim 0.4ec^2 B$ (corresponding to acceleration at almost the gyro-time). This is sufficient to achieve the necessary high energies in a time interval shorter than the (comoving frame) variability time scale.

The discovery of TeV emission from nearby BL Lacertae objects entails an important implication regarding the distance of the γ -ray emission zone from the central accretion flow. In the framework of a unified model for AGN, in which the difference between moderate-luminosity radio galaxies and BL Lacertae objects is due to different orientations of jet and circum-nuclear dust torus with respect to the observer, a strong central near-infrared radiation field is expected from the warm (~ 1000 K) inner edge of the dust torus with a thickness of a few parsecs. Owing to this warm dust torus, TeV γ -rays emitted from within the central parsec (predicted in external photon inverse-Compton models) are converted into pairs and degraded to lower energies (Mannheim 1993b, Protheroe & Biermann 1996). Furthermore, the rapid variability of the TeV γ -ray emission from Mrk421 on a time scale of hours and its correlation with emission at lower photon energies (see contribution by M. Dietrich, this volume) contradict the predictions of the Blandford & Levinson (1995) pair-induced cascade model in which the size of the γ -ray emission zone increases with photon energy.

Thus, it appears that the hadronic models compete with synchrotron-self-Compton (SSC) models in explaining the TeV γ -ray emission from nearby blazars. Fitting the

multifrequency spectrum of Mrk421 with either model yields very different values of the magnetic field strength. Whereas Protheroe (1996a) and Mannheim (1996) find values of 30 and 40 G, respectively, the SSC model of Stecker et al. (1996) yields 0.2 G. The difference by a factor of 200 has important physical implications. The apparent nonthermal luminosity of Mrk421 in bright states is $\sim 5 \cdot 10^{45}$ ergs s $^{-1}$ in the UV-to-soft-X-ray band which corresponds to an emitted luminosity of the order of $\sim 10^{42} \delta_{10}^{-4}$ ergs s $^{-1}$ owing to Doppler boosting with $\delta_{10} \sim \delta/10$. In order to produce the observed emission, the kinetic luminosity of the jet in Mrk421 must be at least $\sim 10^{43}$ ergs s $^{-1}$ (assuming a radiative efficiency of 10%). Hence it follows that the SSC (comoving frame) magnetic field strength of 0.2 G at $r \sim 3 \cdot 10^{15}$ cm is insufficient to confine the jet. On the other hand, to keep the jet radius small even at a distance of more than one parsec away from the black hole magnetic jet collimation is required. External pressure confinement would overproduce X-rays by its free-free emission and the half-opening angle $\phi \propto 1/\gamma_j$ of a free jet would correspond to a jet Lorentz factor of $\gamma_j > 10^3$. A jet with a Lorentz factor larger than ~ 10 cannot escape the central parsec owing to the Compton drag. Another argument against low magnetic field values at the milliparsec transverse scale is that the jets in Fanaroff-Riley type II galaxies with kinetic luminosities of $\sim 10^{46}$ ergs s $^{-1}$ still have magnetic field strengths of 100-300 μ G at the kiloparsec transverse scale (Meisenheimer et al. 1989, Harris et al. 1994). An adiabatic compression of these fields ($B_{\perp} \propto r^{-1}$) yields $\sim 100 - 300$ G at the milliparsec scale. Scaling with the jet luminosity $B \propto \sqrt{L}$ then yields a (comoving frame) field strength of the order of ~ 10 G for the γ -ray emitting zone in the jet of Mrk421. It is obvious that a detection of blazars at energies above TeV would require still lower magnetic field strengths in the SSC models which would make the problem even more severe than it already is.

The hadronic emission models predict emission above TeV (e.g., Mannheim et al. 1996) and if it were absent, this would rule out the hadronic emission models. Cosmic absorption of γ -rays by pair production in collisions with low-energy diffuse background photons, however, represents a major obstacle for this crucial experiment. Nevertheless, a surprisingly strong γ -ray flux has been tentatively detected with HEGRA at 50 TeV by co-adding the events from the positions of the nearest blazars for which cosmic absorption by collisions with diffuse $\sim 100 \mu$ m photons is expected to be lowest (see contribution by H. Meyer, this volume). According to the hadronic emission models, electromagnetic power injected at much higher energies than TeV is reprocessed by a synchrotron cascade towards lower energies. It depends on the pair creation opacity of the emission region for $\gamma + \gamma \rightarrow e^+ + e^-$ below which energy the reprocessed photons emerge. In the proton blazar model (Mannheim 1993a), synchrotron emission by accelerated electrons is calcu-

lated for all jet radii from r_{ir} to some $r_{\text{r}} > r_{\text{ir}}$, i.e. from the radius where the infrared photons become optically thin to the much larger radius where the low-frequency radio photons are produced. Cascade radiation was considered only from the radius r_{ir} , since the infrared photons are the most important target photons for the accelerated protons. At r_{ir} , the turnover energy is $\sim \text{TeV}$ and the cascade spectrum above TeV should steepen by one power compared with the sub-TeV spectrum owing to the energy-dependent pair-creation opacity. This is in accord with recent measurements of Mrk421 with the HEGRA air-Čerenkov telescopes (Petry et al. 1996) and justifies the assumption that the cascade emission is dominated by emission from r_{ir} . However, cascade emission above TeV from an inhomogeneous jet at $r > r_{\text{ir}}$ is still possible and could produce additional γ -ray components. Reliable estimates of the γ -ray flux above TeV require further calculations of proton-initiated cascades for the entire jet. The emission above TeV would then be less variable than the emission at TeV – analogous to the effect of an increasing γ -ray photosphere invoked in the pair-induced cascade model of Blandford & Levinson (1995), albeit at higher energies.

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